Antennas and Other Electromagnetic Applicators in Biology and Medicine

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Invited Paper

Medical and biological applications of antennas may be classified into two broad groups: 1) therapeutic, and 2) informational (including diagnostics and measurement of material electromagnetic (EM) properties). Most of these applications involve electromagnetic coupling into or out of the body, which requires a device such as an antenna or other applicator. A common characteristic of many applications is the difficulty of coupling electromagnetic energy into the interior of the body without damaging the surface. Rapidly increasing computing power and new developments in numerical electromagnetic techniques are expected to have a great impact on the use of electromagnetic devices in medicine and biology.

I. Introduction

Studies of electromagnetic (EM) field interactions with biological systems date back at least to the 1700's when Galvani and Volta, among others, experimented with electrical effects in frog's legs, and Mesmer used magnets to treat patients. Since that time, both the electrical processes inherent in biological systems and various medical and biological applications of EM fields have been studied extensively. Recent increases in computing power and the development of numerical EM techniques are expected to have a great impact on EM applications in biology and medicine. Techniques such as the finite-difference time-domain and the finite-element methods are being used both to give new understanding and to develop better devices.

Medical and biological EM applications may be classified into two broad groups: 1) therapeutic, and 2) informational (including diagnostics and measurement of material EM properties). Examples of therapeutic applications include diathermy, hyperthermia for cancer therapy, rewarming of hypothermic patients, enhancement of bone and wound healing, nerve stimulation and neural prosthesis, microwave angioplasty, treatment of benign prostatic hyperplasia, and cardiac ablation. Some examples of informational applications are imaging (including electrical impedance, microwave, and nuclear magnetic resonance imaging), measurement of lung water content, tumor detection, and personnel dosimetry. Studies of how EM fields interact with biological systems (EM bioeffects) are other examples of informational applications.

Most of these medical and biological applications involve EM coupling into and/or out of the body. This coupling usually requires some device, such as an antenna, to transmit a signal into a body or pick up a signal from a body. At lower frequencies, the device is often called an applicator instead of an antenna, since it is usually short compared to a wavelength and does not function like a radiating antenna. At higher frequencies, the device is usually some form of traditional radiating antenna. In this paper, "applicators" will often be used synonymously with "antennas."

In many biological and medical applications, the antenna operating conditions are different from the more traditional free-space, far-field conditions. Often the near-field and mutual interactions dominate, and the antenna environment is usually lossy. These conditions sometimes produce unexpected results, as illustrated by the example shown in Fig. 1, a two-dimensional model of an electrical sheet dipole (dipole in which the width of the conductor is large compared to the length) separated by an air gap from a rectangular biological body consisting of a layer of fat over a large region of muscle tissue. The length of the antenna is equal to a half-wavelength in the muscle material at 27 MHz. We calculated the EM fields produced by the sheet dipole using the finite-difference time-domain (FDTD) method for two cases: 1) zero thickness of both the fat layer and air gap (antenna directly against muscle) and 2) 1-cm thickness of fat and air [1].

In the first case, the half-wavelength (in muscle) antenna radiates into the muscle material with essentially no radiation into the air space opposite the muscle. This would be expected, since at 27 MHz the wavelength in muscle is about 11 times smaller than in air, which makes the antenna electrically short in air. In the second case, we expected that since the fat and air gap are both small

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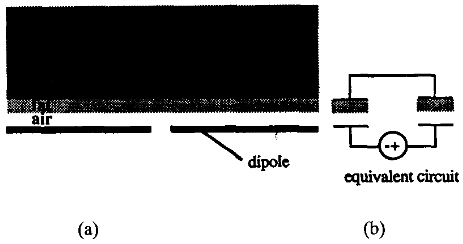

Fig. 1. Two-dimensional model of a dipole radiating into a biological body.

compared to a wavelength, both in muscle and in air, that the fat and muscle would perturb the radiation into the muscle only slightly. The calculations showed, however, that the antenna behaves quite differently. The electric fields (E fields) are very strong and nearly spatially uniform in the air gap and fat with almost no radiation in the muscle, and the current distribution along the antenna is essentially linear with distance from the center, not sinusoidal as expected for a half-wavelength antenna. This is all consistent with the model shown in Fig. 1(b). The antenna behaves more like a capacitor than a radiating antenna. The muscle material, because of its relatively high conductivity (typically 0.612 S/m at 27 MHz), acts like the bottom plate of a capacitor having two dielectric layers, air and fat. The voltage applied at the dipole center excites two capacitors in series.

Assuming a typical sinusoidal current distribution along the dipole or neglecting mutual interaction between the dipole and the body would have given very wrong results in this example. These results illustrate the need for numerical EM methods like the FDTD and finite-element methods in analyzing and designing antennas and applicators for biological and medical applications, and the impact that increased computing power can have on the work. This example also typifies a common characteristic of many medical and biological applications: the difficulty of coupling EM energy into the interior of a biological body without damaging the surface.

In what follows, some recent work in the use of EM applicators (antennas) in biology and medicine, with more space devoted to that involving the more antenna-like applicators, is summarized. Since space limitations preclude a comprehensive description of what has been done, only some representative works are cited.

II. Therapeutic Applications

A. Hyperthermia for Cancer Therapy

Hyperthermia (increasing the body temperature to 41°C or higher) was used to treat cancer patients as early as 1893 by increasing patient temperature through administering bacterial toxins, and EM diathermy was used to produce hyperthermia as early as the 1920's [2]. Much effort has been devoted during the last 20 years to using modern methods of electromagnetics in designing devices to heat tumors.

The objective in hyperthermia therapy is to heat tumors uniformly to the desired temperature and maintain that temperature for a given time in spite of the body's attempt to maintain normal body temperature by its thermoregulatory systems. Heating internal tumors is difficult. Consideration of the plane-wave penetration depth, defined as the depth at which the plane-wave power density is 1/2 that at the surface, gives a good idea of what the limitations are. In muscle tissue the plane-wave depth of penetration is less than 1 cm at 2450 MHz, about 1 cm at 915 MHz, and about 5 cm at 27 MHz. Since finite applicators typically produce less penetration than plane waves, heating a deep lying tumor at these frequencies would overheat the surface, and operation at lower frequencies therefore seems desirable. At low frequencies, though, the wavelength is so long that the energy cannot be localized to a small region, and only large regional heating can be obtained. Worse than that, at low frequencies, the applicator will be electrically small if its physical size is manageable, and near fields will dominate. Since near fields decay rapidly with distance away from the applicator, dominant near-fields often overheat the surface. Consequently, practical heating of internal body tumors without overheating the surface is very difficult at any frequency. More details about the fundamental limitations and trade-offs faced in designing EM systems for hyperthermia are summarized in many review articles, for example [3].

1) Noninvasive Applicators: Noninvasive (not penetrating the body) applicators may be classified as belonging to three main groups: 1) E-type (low-frequency) applicators, which produce mainly an E field that heats the tissue, 2) H-type (low-frequency) applicators, which produce mainly a magnetic field, which in turn induces the E field that heats the tissue, and 3) radiative applicators.

a) E-type applicators: Capacitor-plate applicators are typical E-type applicators. These applicators are usually operated at either 13.56 MHz or 27.12 MHz, two of the frequencies assigned to industrial, scientific, and medical use (ISM frequencies). Capacitive applicators heat deep tissue well, but they usually produce large components of E field normal to the fat muscle interface, which overheat the fat because boundary conditions require the normal E fields at the interface to be discontinuous by the ratio of the permittivities, and since fat has a lower permittivity than muscle, the E field in the fat is higher [3]. Bolus water conductivity and size of the capacitor plates affect internal heating patterns [4]. With multiplate capacitor configurations [5], internal heating patterns can be adjusted by changing the relative voltages applied to the various plates. Ring capacitors can produce deep internal heating without overheating the surface if a proper gap is maintained between the rings and the body surface [6].

The helical-coil applicator is like an H-type applicator in some respects, but its heating characteristics seem to be more like an E-type applicator, since the strong E field produced between the turns of the coil is mainly responsible for tissue heating. Large pitch angles (coils more parallel to the axis) produce better results [7]. A surface semicylindrical helical coil heats well internally, but tends to overheat the surface [8].

b) H-type applicators: Perhaps the simplest H-type applicator is a single coaxial current loop. A device called the magnetrode consists of a single sheet coaxial current loop [9]. Since the coaxial current loop produces eddy-current type E fields that circulate around the axis of the loop, heating in the center of the body is minimal. Generally speaking, H-type applicators seem not to couple as strongly to the body as E-type applicators, and relatively high currents are usually needed to get adequate heating.

Three- and five-ring coaxial current applicators give increased depth of heating over single ring applicators at 13 MHz [10]. A nonencircling single current loop with the edge next to the body, which is equivalent to a magnetic-dipole, is another H-type applicator [11]. A twin-dipole version has also been studied [12]. Calculated results for a folded-loop variation of such applicators showed increased depth of penetration over a single loop [13]. Others used a sheet-current loop [14]. All of these H-type applicators have the advantage that they produce an E field mostly tangential to the fat, which therefore does not overheat the fat. Since most of them are designed to operate at ISM frequencies of 13.56, 27.12, or 40 MHz, the depth of penetration is typically a few centimeters.

c) Radiative applicators: Various kinds of open-ended waveguide applicators, some loaded with dielectrics to provide better impedance matching and coupling to the body, have been studied over the years. These single-waveguide applicators generally produce penetration less than the theoretical plane-wave penetration. Although focusing is difficult because of the high loss in tissue at the higher frequencies, incorporating a lens in a 192×150 mm aperture waveguide at 430 MHz resulted in penetration about twice that of a conventional waveguide applicator [15]. Whether hot spots would occur in fat layer and how body inhomogeneities would affect the focusing apparently was not studied. Microstrip radiators are attractive because of their compactness. Penetration depths of 1.6 cm at 433 MHz and 1.1 cm at 915 MHz have been obtained in a homogeneous muscle phantom with a microstrip loop that has a shorting pin opposite the feed [16]. Nothing was said in this work about whether hot spots occur in the fat.

In quite a different approach, a large (6 m wide) waveguide applicator in which the patient is inserted through a hole in the waveguide, thus acting like a lossy waveguide post, has been analyzed at frequencies between 25 and 100 MHz and shown to produce good central heating at the lower frequencies [17]. Good central heating was also achieved in a 70-MHz coaxial TEM applicator, in which the center conductor is a hollow water-filled cylinder large enough to contain the patient [18]. The TEM fields are produced by a gap in the inner conductor near the region of the patient to be heated.

The idea of using phased arrays to provide focusing and improve the penetration depth is attractive, but high loss in tissue at the high frequencies where a small spot size could be achieved limits the focusing. Phased arrays at lower frequencies can provide better penetration, but not a small spot size because the wavelength is too long. An annular-phased array (APA) consisting of two side-by-side arrays of eight dielectrically loaded apertures operating at frequencies from 55 to 110 MHz [19] has been used extensively to provide a deep regional heating pattern that can be adjusted to some extent by phasing the radiators. Operation in this frequency range provides deep penetration, but not a small focused spot. A second generation version called the Sigma 60 uses eight electric dipoles as radiators. A recent article reviews various kinds of phased arrays [20].

2) Invasive Applicators: Invasive applicators can produce more uniform and controllable heating patterns than noninvasive applicators, but they require some kind of implantation in the tissue, which is not feasible for all tumors. Electrical invasive applicators are of three basic types: 1) arrays of needles that produce RF localized current fields (LCF), 2) radiating microwave antennas, and 3) inductively heated ferromagnetic seeds. Stauffer recently reviewed invasive applicator work [21].

In the RF LCF systems, RF currents produced by voltage sources connected between needle pairs, or between one set of needles and another set, produce ohmic heating. The heating pattern is affected by tissue inhomogeneities, since the current will tend to follow the paths of least resistance. Parallelism of the needles also affects uniformity of the pattern. Since current density concentrates near needle surfaces, the heating is strongest there, decreasing as the current spreads out between the needles. Heating patterns have been adjusted by switching sources repeatedly between alternate pairs of needles and by dielectric coatings on a portion of each needle.

Implanted radiating microwave antennas, either singly, or in arrays, both phased and nonphased, have been used extensively for heating certain kinds of tumors. Where it is feasible to implant antennas, well controlled heating patterns can be achieved. Implanted microwave antennas heat both through ohmic and dielectric losses. A typical implanted antenna consists of coaxial cable with the center conductor extended. Variations include steps in the diameter of the extended center conductor, various dielectric coatings on the center conductor, and helical coils wound around the center conductor. Attempts have been made to increase heating near antenna ends, where it tends to be minimal. Radiating microwave antenna systems have also been placed in body cavities, instead of implanted directly in body tissue [22], [23].

In the third method, ferromagnetic segments (or seeds) are implanted and then heated by an externally applied low-frequency (less than 500 kHz) magnetic field. The overall heating pattern is a function of the size, shape, and ferromagnetic properties of the seeds. Advantages are that no connections between the source and the seeds is required, and the size, shape, and properties of the seed can be chosen to optimize the heating pattern, but a strong magnetic field is required to produce the heating.

B. Other Therapeutic Applications

Antennas and other EM applicators similar to those used for hyperthermia, particularly capacitive and inductive applicators, have been used for diathermy [24]. EM applicators can produce deeper heating than methods that simply heat the body surface and rely on thermal conduction to carry the heat to the deeper tissues. Similar applicators have also been used to rewarm hypothermic patients. If peripheral tissues are warmed while the heart is still cold, as happens with conventional rewarming, the warmed peripheral tissues demand increased circulation that overloads the still cold heart. A better method is to rewarm the heart first by EM techniques, which increases cardiac output and circulates warmed blood to the peripheral tissues without overloading the heart [25]. Inserted microwave devices have also been used to treat benign prostatic hyperplasia by EM heating [26].

RF EM energy conducted through a small coaxial cable inserted in a catheter into the heart has been used to ablate ventricular myocardium to treat some cardiac conditions [27]. In combination with conventional balloon angioplasty, Rosen *et al.* used microwave heating produced by a microwave antenna at the end of a coaxial cable in an artery to soften arterial plaque to help enlarge the lumen of narrowed arteries [28]. Stimulating nerves by applying external magnetic fields without internal electrodes is being studied [29]. The EM design challenge here is how to design an applicator to get strong enough fields deep enough into the tissue to stimulate the nerves.

III. Informational Applications

Although magnetic resonance imaging (MRI) is a field of research by itself, the design of the coils to produce the RF magnetic fields is a crucial element of an MRI system. The quality of the image depends on the uniformity of the magnetic fields inside the body to be imaged. At frequencies in the lower MHz range, where the size of the coil is small compared to a wavelength, a saddle-shaped coil has been traditionally used with great success. As the MRI systems are designed to operate at higher magnetic field strengths (and therefore at higher frequencies) to improve the intrinsic sensitivity, the inductance of the traditional saddle coil becomes too high to resonate. Consequently, other structures, such as the slotted resonator, have been developed to operate at frequencies higher than 100 MHz [30].

Various waveguide and horn apertures have been used in microwave imaging systems. Microwave imaging seems desirable because the contrast in permittivities of different body tissues is high, leading one to expect good contrast in microwave images. The same fundamental limitations that plague the development of hyperthermia applicators also limits microwave imaging, however. To get good resolution requires using frequencies for which the wavelength is short, but at these high frequencies, the attenuation is so high in the body that images are difficult to obtain. Although microwave images of dielectric rods and isolated animal organs have been obtained [31], microwave images are not expected to reach the quality of MRI, for example. Lower-frequency electrical impedance methods have been used to obtain diagnostic information such as total body water, change in water volume, and cardiac function. Electrical impedance tomography can produce images, but with poor resolution [32]. Although electrical impedance methods use electrodes instead of conventional antennas, they are mentioned here because they are an important EM technique.

Microwave radiometry is an interesting application of antennas because it is based on measuring EM fields emitted by the body itself, in contrast to other methods which require applying EM fields to the body. Waveguide and horn apertures are typically used in microwave radiometers that have been used both for breast tumor detection [33] and for measuring changes in lung water content [34]. The breast tumor detection is based on local temperature variations produced by the tumors, and the measurement of lung water changes on the change in emissivity with water content.

Another informational application of antennas is measuring the permittivity of biological objects, which is important both for design of EM systems that interact with biological systems, and possibly for diagnostic purposes. In particular, in-vivo measurement of permittivities can be important, because the permittivity of excised tissue may be different from that of intact tissue in the living animal. Some form of open-ended coaxial antenna or coupler is typically used to measure permittivity in-vivo; this also requires calculating the interaction of the EM fields with the tissue [35].

Antennas have been used in various ways to study the effects of EM fields on biological systems. Special radiating systems have been designed, for example, to couple EM fields into biological samples [36]. More conventional radiating antennas have been used in EM dosimetry (calculation and measurement of EM fields inside irradiated animals) and in studies of organism response to EM irradiation, such as behavioral studies.

IV. Concluding Remarks

Antennas and other EM applicators have been used in many different ways in medicine and biology. Most of these applications involve coupling of the EM fields into and/or out of the body. In this paper, the work has been grouped into two main categories, therapeutic and informational applications. Some of the recent work in these areas has been briefly described. A common characteristic of many of these applications is the difficulty of coupling energy into the deep tissues without damaging the surface of the body. Recent rapid developments in numerical electromagnetic techniques is expected to have great impact on the medical and biological applications of antennas and other EM applicators.

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